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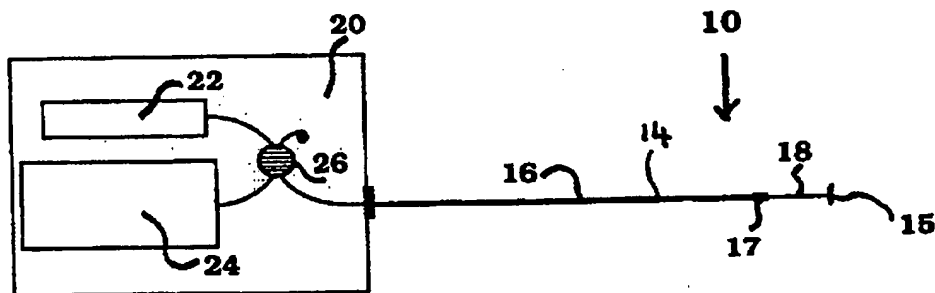


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(54) Title: **OPTICAL SENSORS AND METHOD FOR PRODUCING FIBRE OPTIC MODALMETRIC SENSORS**



(57) Abstract

An optical sensor and a method of producing the optical sensor is disclosed in which a singlemode fibre (14) is fusion spliced to a multimode fibre (18). The multimode fibre is cleaved or polished at a desired location from the splice (17) to localise the sensor, the end (15) of the multimode fibre can be mirrored to reflect radiation back through the multimode fibre so that the radiation re-enters the singlemode fibre for detection by a detector (24). Alternatively, a light source (22) can be coupled to the singlemode fibre and a further singlemode fibre connected to the multimode fibre at the desired location by fusion splicing so that a detector (24) can be connected to the further singlemode fibre for detecting radiation which is passed through the multimode fibre and which has had its property changed in the multimode fibre.

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- 1 -

OPTICAL SENSORS AND METHOD FOR PRODUCING FIBRE OPTIC  
MODALMETRIC SENSORS

This invention relates to an optical sensor and method for producing modalmetric waveguide sensors.

5           Optical devices are commonly used in industry and science and include laser cavities, waveguides, lenses and other optical elements. Such optical devices are used in a variety of instruments and installations.

10           Photonics technology has revolutionised the communications and sensor fields. This is mainly due to the rapid development of opto-electronic devices. A wide variety of glass materials, material-dopants and waveguide structures are available and the present invention relates to a waveguide sensor which is particularly well suited for  
15           detecting and monitoring structural parameters caused by acoustic, mechanical, electrical and magnetic events (i.e. strain, vibration, resonance, acoustic emission, etc.). In particular, the fibre optic modalmetric sensor has been proven to have good potential for vibrational analysis of  
20           structures and for machine condition monitoring applications.

          Presently, there is a very high demand for sensors and systems which provide real-time monitoring of the integrity or condition of machines and structures.  
25           Fibre optic sensors, in particular, are very promising for these applications because of their dielectric properties, their fine size, their ability to be remotely located and, in the case of intrinsic sensors, rapid response times. They also have particular advantages in hazardous  
30           environments. In addition, they have several clear advantages over existing conventional sensing techniques such as bulk optical measurements, potentiometric electrodes, resistive foil gauges and piezo-electric transducers.

35           Engineered structures are usually not monitored in real-time because of the difficulties in incorporating

- 2 -

the sensors into the sensing environment and because of the limitations of the sensors. Optical sensors overcome these difficulties by virtue of their inherent properties. In addition, optical sensors and optical processing systems are extremely fast and do not suffer from electro-magnetic interference (EMI), unlike their electronic counter-parts.

A simplistic definition of the modes that are guided by an optical fibre can be explained as the locus of all the light rays which are launched at different entry angles into the core of the fibre. For any optical fibre the number of modes that will be guided by the fibre is dependent on core size, the ratio of core/cladding refractive indices, and the wavelength of operation.

Multimode optical fibres suffer from optical signal fading and drift due to the random or chaotic nature of the light propagating along the fibre. The optical fibre industry has overcome the inherent weaknesses of multimode fibres by the use of singlemode fibre systems, but these are difficult to handle, and utilise quite expensive components.

The claimed invention overcomes the inherent weaknesses of multimode fibre optic sensors, is easy to fabricate and costs relatively little to assemble.

Optical fibres were found to be very microphonic quite early in the development of fibre optic systems. [Culshaw et al., "Acoustic Sensitivity of Optical Fibre Waveguides", *Electronic Letters*, 13(25), pp. 760-761, 1977] In the simplest configuration, a source of coherent optical radiation is used to launch light into a multimode fibre and a photodetector monitors the transmitted output signal. Loads, vibrations and acoustic signals acting on the multimode fibre causes a change in length, diameter, and refractive index of the fibre, resulting in phase and polarisation modulation of the individual modes supported in the fibre. [Spillman et. al., "Statistical-Mode Sensor for Fiber Optic Vibration Sensing Uses", *Applied Optics*, Vol. 28, pp. 3166-3176, 1989] Each mode is modulated

- 3 -

differently and therefore travels a different path to the end-face of the fibre. The transmitted modes in the fibre combine or interfere at the fibre end-face and the pattern is received by the detector. The observed interference pattern is in the form of a chaotically distributed speckle pattern. Any external perturbations acting on the fibre randomly redistributes the speckle pattern with a resultant amplitude modulation perceived at the detector. Because this arrangement is very sensitive to external variations and the amplitude modulation is generally nonlinearly related to the phase and polarisation modulation, the resultant output signal suffers deep fading and drifting. [Rawson et. al., "Experimental and Analytical Study of Modal Noise in Optical Fibers", *Proceedings: Sixth European Conference on Optical Communication*, pp. 72-75, 16-19 September, 1980] This behaviour limits the use of multimode fibres in systems which require signal stability and reliability.

Researchers have analysed the spatial-temporal coherence function propagation in multimode fibres when propagated by a coherent source of radiation. [De Marchis et. al., "Modal Noise in Optical Fibres", *Proceedings: Sixth European Conference on Optical Communication*, pp. 76-79, 16-19 September, 1980] [Spillman et. al., "Statistical-Mode Sensor for Fiber Optic Vibration Sensing Uses", *Applied Optics*, Vol. 28, pp. 3166-3176, 1989] [Ignatyev et. al., "Fiber Optic Interferometric Sensors Using Multimode Fibers", *SPIE Proceedings: Fiber Optic and Laser Sensors IX*, Vol. 1584, pp. 336-345, 1991] They found that the spatial-temporal coherence function at the multimode fibre end-face is represented as a sum of stationary and non-stationary terms related to the spatial and temporal coherence properties of the optical signal and waveguide. Summarising their calculations, they derived that a multimode fibre with a given index profile possesses spatial coherence filtering properties, even for a spatially incoherent source of input radiation. In

- 4 -

particular, Ignatyev et. al. predicted that the spatial coherence of the radiation that has passed through quite long lengths of multimode fibre (over 2 meters) is spatially stationary and has a coherence radius related to the wavelength (typically 2 to 3  $\mu\text{m}$  at  $\lambda=633\text{ nm}$ ) and fibre numerical aperture. Therefore, the central core region of the multimode fibre end-face with a radius less than or equal to the coherence radius could be considered spatially coherent and stationary. Therefore, if the inner core region of the multimode fibre could be monitored independently from the entire core cross-section, it should yield improved linearity in the amplitude modulation resulting in a reduction in signal fading and drifting.

A number of methods for isolating either individual modes or the inner core region of a multimode fibre have been disclosed in the art. One such method involves placing a singlemode fibre in close proximity to various locations on the end-face of a multimode fibre in order to selectively excite a single or limited number of modes in the multimode fibre and thus stabilise the fibre output. [White and Cooper, "Selective Excitation of the Modes of Multimode Graded Index Fibers", *Proceedings: Sixth European Conference on Optical Communications*, pp. 95-98, 16-19 September, 1980]

In a second method, and the most common known in the art, an external lens and spatial filter arrangement is used to isolate regions of the speckle pattern output of a multimode fibre such that a photodetector can measure the optical power in a given group of modes. Vibration or acoustic emission sensing based on this principle has been successfully demonstrated in numerous application areas. [Fuhr et. al., "Simultaneous Single Fiber Optical Communications and Sensing for Intelligent Structures", *Smart Materials and Structures*, Vol. 1, pp. 128-133, 1992]

[Cosgrave et. al., "Acoustic Monitoring or Partial Discharges in Gas Insulated Substations Using Optical Sensors", *IEE Proceedings-A*, 140(5) pp.369-374, 1993] [El-

- 5 -

Sherif and Ko, "Smart Textile Composites by Co-Braiding of Fiber Optic Sensors", *Proceedings: Ninth International Conference on Composite Materials (ICCM-9)*, Madrid, Spain, Vol. 2, pp.402-404, July, 1993]

5           These prior art methods, however, suffer from a number of disadvantages. Mechanical support is generally needed to align and maintain alignment of the fibre, lens and external spatial filter, therefore increasing the overall bulk and expense of the final system. In addition,  
10   the arrangement would be susceptible to noise and inconsistencies resulting from environmental conditions, ie. temperature fluctuations, vibrations and fouling of optical surfaces. Furthermore, for practical applications, the sensing region of the fibre cannot be localised and,  
15   therefore, the system would suffer from lead-in fibre sensitivity.

          Another significant disadvantage of the prior art methods utilising external spatial filters is that the optical signal is coupled out of the fibre in only a  
20   forward or lateral direction, but not in the reverse direction, as is often required in preferred applications.

          In a third prior art method, Ignatyev et. al. predicted that a narrow core fibre, if coupled directly to the "coherence" radius region of a larger-core fibre, would  
25   perform the function of an optical spatial coherence filter or diaphragm and hence greatly improve the quality of the transmitted beam, ie. improved linearity, reduced signal fading, reduced signal drift, etc. [Ignatyev et. al., "Fiber Optic Interferometric Sensors Using Multimode  
30   Fibers", *SPIE Proceedings: Fiber Optic and Laser Sensors IX*, Vol. 1584, pp. 336-345, 1991] However, their suggested embodiments of the sensors still required the optical signal to be coupled out of the fibre in only a forward or lateral direction, but not in the reverse direction, as is  
35   often required in preferred applications.

          Soon afterwards, Tapanes and Rossiter selected and monitored a small diameter, central region of a

- 6 -

multimode fibre end-face by placing a singlemode fibre diaphragm in close proximity to the multimode fibre and found that the concept was sound. The response of the multimode fibre, which was previously chaotic, had become stable and displayed a good quantitative response. Furthermore, by extending the singlemode fibre to a sufficient length the signal to noise ratio (SNR) was found to be greatly improved. [Tapanes and Rossiter, "Practical Application of Fibre Optic Sensors to Engineered Structures", *Proceedings: Australian Conference on Optical Fibre Technology-17 (ACOFT-17)*, Hobart, Tasmania, Australia, pp. 210-213, Nov/Dec, 1992] [Tapanes and Rossiter, "Practical Application of Fibre Optic Sensors to Engineered Structures for Real-Time, Nondestructive Evaluation Using a Composite Material Patch", *Proceedings: Ninth International Conference on Composite Materials (ICCM-9)*, Madrid, Spain, Vol. 2, pp. 405-412, July, 1993]

Tapanes and Rossiter constructed a multimode sensor using a singlemode pigtailed laser diode operating at  $\lambda=670.6$  nm. The laser diode pigtail was FC-connected to one port of a 633 nm singlemode, 3 dB (2X2) fibre optic coupler. A 1300 nm singlemode fibre with 9/125  $\mu\text{m}$  core/cladding diameter and mirrored end-face was mechanically coupled to one of the sensor ports of the (2X2) coupler using a Dorran mechanical splice. The other unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was ST-connected to a photodiode. The 1300 nm singlemode fibre was used as the multimode (approximately 4 modes) sensing fibre and the 633 nm, 3.7  $\mu\text{m}$  core diameter fibre-lead of the coupler was used as a diaphragm as well as to deliver and return the optical signals to/from the sensing region. The sensor lengths used were typically 70 mm in length.

Tapanes and Rossiter overcame some of the disadvantages of prior art techniques by using a mechanical splice to maintain alignment of the single and multi moded fibres by butting the fibres against one another and



- 7 -

mechanically locking them in that position. The precision V-groove of the mechanical splice and the identical overall diameters of the two fibres ensured that the core of the singlemode fibre was maintained in alignment with the central region of the multimode fibre end-face. Furthermore, by mirroring the end-face of the multimode fibre, the optical signal returned to the optical system components in the reverse direction, as is often required in practical applications. This arrangement resulted in a so called "multimode fibre optic interferometer" with very good response linearity, as well as reduced drift and signal fading.

This prior art method, however, suffers from a number of disadvantages. The mechanical splice requires mechanical support to prevent environmental conditions from affecting the fibres' alignment and separation within the splice cavity. This disadvantage requires that the mechanical splice be located well away from the sensing region and that the multimode fibre sensor be of sufficient length to allow for this. Therefore, the localisation of the sensor in this prior art technique is limited to relatively long lengths (usually 50 mm and greater). Furthermore, mechanical splices are manufactured to couple fibres of standard diameters (125  $\mu\text{m}$ ). This limits the choice of optical fibre to standard telecommunication types, which may not necessarily be the most appropriate for a specific sensing application. In addition, mechanical splices do not couple fibres of different diameters and therefore, once again, limits the possible combination of fibres used.

The present invention provides a method for producing a sensor, including:

providing a singlemode optical fibre formed from a waveguide material and having a fibre core;

providing a multimode waveguide and having a waveguide core;

fusion splicing the singlemode fibre and

- 8 -

multimode waveguide so that centres of the cores of the singlemode fibre and multimode waveguide are aligned and remain fixed at the splice; and

5           cleaving or polishing the multimode waveguide, after the fusion splicing, at a desired location spaced from the splice to localise the sensor.

10           In the sensor according to the invention a singlemode of electromagnetic radiation is launched into the singlemode fibre from a light source such as a laser and propagates along the singlemode fibre. When the light source reaches the multimode waveguide the singlemode can branch out into multiplemodes within the multimode waveguide so that when the multimode fibre experiences a change due to the change in the environment it is  
15           monitoring, properties of the electromagnetic radiation in the multimode waveguide can be altered. Light which has had its property altered in the multimode waveguide enters the singlemode fibre from the multimode waveguide for detection by the detecting device. Cleaving or polishing  
20           of the multimode waveguide for application of a mirroring material to reflect radiation back to a detector or fusion splicing of a singlemode fibre for enabling light to pass from the multimode waveguide to the singlemode fibre and then to a detector without reflection enables size of the  
25           sensing portion, namely the multimode waveguide, to be controlled so that the sensing portion can be made considerably smaller than in prior art devices.

30           Preferably the singlemode and multimode fibres are prepared prior to fusion splicing by cleaving or polishing ends of the singlemode fibre and multimode waveguide to establish flat smooth surfaces at the ends of the singlemode fibre and multimode waveguide which are to be fusion spliced.

35           Preferably the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.

          Preferably the flat smooth surface at the desired

- 9 -

location is coated with a mirroring material to reflect radiation back through the multimode waveguide and then the singlemode fibre to a detecting device. However, in another embodiment the cleaved or polished multimode waveguide is fusion spliced at a desired location to a singlemode fibre which in turn is coupled to a detecting device.

Preferably the singlemode fibre is coupled to a light source, and a detecting device.

Preferably a plurality of multimode waveguides and singlemode fibres are fusion spliced in end-to-end relationship to form a quasi-distributed sensor.

In other embodiments a plurality of singlemode fibres are fusion spliced to respective multimode waveguides and the plurality of singlemode fibres are connected to a coupler which in turn is connected to a further singlemode fibre to form a multiplexed sensor.

Preferably the multimode waveguide is a multimode fibre.

Thus preferably the invention may be said to reside in a method for producing a waveguide sensor, including, but not limited to, the steps of:

Preparing a singlemode and a multimode fibre by cleaving or polishing their ends so as to establish a flat, smooth surface. After taking necessary precautions to remove any contaminants from the cleaved or polished fibre end-faces, the fibres are placed end-to-end in a fusion splicing apparatus and fused together using the appropriate or desired fusion arch times and currents. The fusion splicing procedure may be repeated a number of times if necessary. Although it is not imperative, a preferred procedure for splicing the fibres involves setting the fusion splicing parameters such that the fibres are abruptly fused and not wholly fused in a tapered-like manner, such that a visible line separating the fibres is observable. In this manner, the smaller core of the singlemode fibre does not taper or merge with the larger

- 10 -

core of the multimode fibre and, therefore, essentially retains the original diaphragm size. The core and overall diameters of the fibres is not limited and translation stages and/or V-grooves may be used on the fusion splicing apparatus to centrally align the cores of the two fibres before the fusion splicing procedure. Different combinations of single and multi mode fibres may require a different or unique set of fusion splicing parameters.

Preparing or connectorising the free end of the singlemode fibre in any manner which facilitates attaching, connecting or coupling the singlemode-fibre-part of the sensor to the appropriate combination and arrangement of light source, coupler, photodiode and signal processing electronics.

Cleaving or polishing the multimode fibre at any location after the fusion splice so as to establish a flat, smooth surface. The position of the cleave or polished surface establishes the localised length or sensing region of the sensor. Therefore, it is possible to produce localised sensing lengths less than 1 mm long. There is no limit to the maximum length, other than those imposed by the optical attenuation and scattering of the waveguide material, by induced microbend losses or by limitations of the optical components in the system. After taking necessary precautions to remove any contaminants from the cleaved or polished multimode fibre end-face, a selected portion of the fibre, including the end-face of the multimode fibre, is mirrored with a suitable mirroring material (ie.. a metal or dielectric material).

A preferred method for mirroring the multimode fibre end-face involves placing the fibre in a vacuum system and the prepared fibre end-face is then coated with a metallic material such as Au, Ag, Al or Ti or a dielectric material such as  $\text{TiO}_2$ . This coating can be prepared by using thermal evaporation, electron beam evaporation or sputtering. Other coating or mirroring materials and techniques may also be utilised.

- 11 -

In an optional embodiment, the manufactured sensor and/or the exposed fusion spliced region may be protected by encapsulating or coating the desired region in a suitable material (ie. ultraviolet acrylate, epoxy, etc.).

Any suitable light source, coupler and photodetector may be used with the sensor. The required optical properties of the light source are such that light may be launched into and propagated in the singlemode waveguide. For localisation, the light propagated in a singlemode fibre should remain singlemoded during the entire period of travel in the singlemode fibre. Once the light is launched into the multimode fibre from the singlemode fibre, several modes may be excited and the multimoded fibre will be sensitive to various parameters. Once the light is launched back into the singlemode fibre from the multimode fibre, only a single mode is supported and travels to the optical components of the system. Lead-in/lead-out fibre desensitisation and sensor localisation is achieved in this manner. In practical applications, the singlemode fibre should be made sufficiently long to attenuate all cladding modes in order to improve the signal-to noise ratio.

The invention also provides a sensor including:  
a singlemode optical fibre formed from a waveguide material and having a fibre core; and  
a multimode waveguide and having a waveguide core, the multimode waveguide being fusion spliced to the singlemode optical fibre so that centres of the cores of the singlemode waveguide and multimode fibre are aligned and remain fixed at the splice; and

wherein the multimode waveguide is cleaved or polished, after fusion splicing, at a desired location spaced from the fusion splice to localise the sensor.

Preferably the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.

- 12 -

Preferably the flat smooth surface at the desired location is coated with a mirror material to localise the sensor.

5 In another embodiment the cleaved or polished multimode waveguide is fusion spliced to a further singlemode fibre which is coupled to a detecting device.

Preferably the sensor includes a light source and a detecting device.

10 In the preferred embodiment of the invention the light source and detecting device are coupled to the singlemode fibre so that radiation, in use, is launched into the singlemode fibre and propagates along the singlemode fibre and also along the multimode waveguide wherein properties of the radiation are altered due to  
15 changes in a parameter which is to be monitored, and the radiation is reflected from the mirroring material back along the multimode waveguide and singlemode fibre for detection by the detecting device.

20 In some embodiments of the invention a plurality of multimode waveguides and singlemode fibres are fusion spliced end-to-end to provide multi-distributed sensors. In other embodiments a plurality of singlemode fibres are fusion spliced to multimode waveguides and the singlemode fibres are coupled to a coupler which is in turn coupled to  
25 a further singlemode fibre to produce a multiplexed sensor.

The waveguide sensors according to this invention can be used in real-time to monitor engineering structures and fabricated items. Their small size enables them to be used in difficult-to-reach areas or embedded non  
30 intrusively in an object for in-situ monitoring. The concept of incorporating the waveguide sensors into a patch body provides protection for the sensor and allows the patch body to be adhered to the surface of existing or completed structures.

35 Utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor also enables monitoring to take place in a

- 13 -

non-destructive manner. Thus, the sensor is not necessarily fractured or destroyed in order to monitor the desired parameter.

5 The effective sensing length of the waveguide sensor can be varied for either point or integrated sensitivity. Multi-point sensing can be achieved by quasi-distributed, distributed or multiplexed configurations.

10 Preferably the waveguide comprises at least one optical fibre and/or at least one optical fibre device. In some embodiments of the invention the waveguide may merely comprise an optical fibre without any additional sensing elements. However, the optical fibre can include sensing elements at its end or along its length and those sensing  
15 elements can comprise devices which will respond to a change in the desired parameter in the environment of application and influence the properties and characteristics of the electromagnetic radiation propagating in the waveguide to thereby provide an  
20 indication of the change in the parameter.

The waveguide or waveguides may be formed from any glass material, hard oxides, halides, crystals, sol-gel glass, polymeric material or may be any form of monolithic substrate.

25 Electro-optic devices, acousto-optic devices, magneto-optic devices and/or integrated optical devices may also be utilised in the sensing system.

Preferably the fusion splicing takes place in a fusion splicer or by laser welding techniques, or by any  
30 other technique to fuse the multimode waveguide and singlemode fibre.

Preferred embodiments of the present invention will be further illustrated, by way of example, with reference to the following drawings in which:

35 Figure 1 is a view showing an embodiment of the invention illustrating fusion splicing and mirroring;

Figure 2 is a more detailed view of the

- 14 -

embodiment of figure 1;

Figure 3 is a view showing a further embodiment of the invention;

Figure 4 is a view showing a still further embodiment of the invention; and

Figure 5 is a view showing yet a further embodiment of the invention.

With reference to figure 1, a singlemode fibre 14 and a multimode fibre 18 are prepared by cleaning their ends so as to establish a flat, smooth surface. After taking necessary precautions to remove any contaminants from the cleaved fibre end-faces, the fibres are placed end-to-end in a fusion splicing apparatus and fused together at 17 using the appropriate or desired fusion arch times and currents. The multimode fibre 18 is then cleaved at any location after the fusion splice 17 so as to establish a flat, smooth surface. The position of the cleave or polished surface establishes the localised length or sensing region of the sensor 12. After taking necessary precautions to remove any contaminants from the cleaved multimode fibre end-face, a selected portion 15 of the fibre, including the end-face of the multimode fibre, is mirrored with a suitable mirroring material (ie., a metal or dielectric material).

In the embodiment of figure 2, a fibre optic modalmetric sensor 10 according to the preferred embodiment comprises a multimode fibre 18 which is mirrored on its end-face 15 and fusion spliced 17 to a singlemode fibre patch cord 16. The free end of the fibre optic modalmetric sensor 10 can be adhered to an engineering structure or manufactured article. The singlemode fibre patch cord 16 is coupled to instrumentation 20 which includes a light source 22, coupler 26 and a detector and signal processing unit 24. The patch cord 16 can be of any desired length, and indeed up to several kilometres, so the instrumentation 20 can be located remote from the multimode fibre 18 which forms the sensing element of the sensor 10. The light



- 15 -

source 22 provides light which is propagated along the singlemode fibre 14 in the singlemode fibre patch cord 16 and, which in the embodiment of figure 2, is reflected back along the optical fibre for detection by the unit 24.

5                   However, in other embodiments the detecting unit 24 could be located at the end of the optical fibre and the transmitted wave could merely be detected by the unit 24 without the need for reflection. The propagated light in the multimode fibre 18 which is eventually detected by the  
10                   detector unit 24 has its properties and characteristics altered by a change in a desired parameter which is to be monitored.

                  In this embodiment and the other embodiments to be described in the following description, the multimode  
15                   fibre 18 and a small part of the singlemode fibre 14/patch cord 16 is located on a patch body (not shown) of host material to enable the sensor to be conveniently attached to a structure or the like.

                  In the embodiment of figure 3, a singlemode  
20                   optical fibre patch cord 16 is coupled to the light source 22. A multimode fibre 18 is then fusion spliced to the singlemode fibre 16 in the same manner as described with reference to figures 1 and 2. The other end of the multimode fibre 18 is cleaved and prepared in the manner  
25                   referred to above and fusion spliced to a further singlemode fibre 14. The singlemode fibre 14 is fusion spliced to a multimode fibre 18 which is in turn is fusion spliced to a singlemode optical fibre patch cord 16 which is coupled to the detector and signal processing device 24.  
30                   In this embodiment of the invention a quasi-distributed sensor is produced which has sensing portions formed by the two multimode fibres 18 wherein the propagated electromagnetic radiation is received by the detector 24 at the end of the optical path rather than by reflecting the  
35                   radiation back from a mirrored end 15 as in the embodiment of figure 2.

                  In the embodiment of figure 2, the patch cord 16

- 16 -

including the singlemode fibre, connected to detector 24, could be replaced with a multimode fibre. Depending on the length of the multimode fibre, results may not be as good as the arrangement shown in figure 2 because of drift or interference in the multimode fibre which replaces the patch cord 16.

In the embodiment of figure 4, a quasi-distributed sensor arrangement 30 is illustrated. This arrangement is made possible by fusion splicing 17 insensitive singlemode fibre 14 sections between the sensitive multimode fibre 18 sections.

In the embodiment of figure 5, a multiplexed fibre optic modalmetric sensor system 40 is illustrated. A (1XN) star coupler 42 joins the singlemode optical fibre patch cords 16 to one individual singlemode optical fibre patch cord 44. This type of configuration would be capable of mapping parameter fields.

The primary applications of the fibre optic modalmetric sensor according to the preferred embodiments of this invention is in structural integrity monitoring and machine condition monitoring. The sensor could be used to monitor a wide variety of structures and machinery, for example: metal or composite material aerospace structures, satellites, marine vessels, submersible vessels, storage vessels, off-shore structures, pipelines, chemical storage containers, power transformers, power generators, hydro electric dams, gearboxes, motors, compressors, buildings, bridges, etc. Other parameters could also be monitored depending on the type of waveguide or sensor arrangement employed.

The sensors are capable of monitoring parameters in a reliable and non destructive manner. In other words, the sensor waveguide does not rely on failure, fracture, breakage or any other form of permanent, irreversible change.

Preferred embodiments of the invention have been tested illustrated by the following examples. The sensors

- 17 -

were constructed in order to determine the feasibility of producing localised fibre optic modalmetric sensors with relatively short sensing lengths. Parameters monitored with the fibre optic modalmetric sensors included strain, vibration, structural resonance, frequency analysis, acoustic emission, sound, temperature and proximity. Not all of the results obtained to date are detailed in the following examples.

Example 1:

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at  $\lambda=670$  nm. The laser diode pigtail was fusion spliced to a 633 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 3.5/125  $\mu\text{m}$  core/cladding diameter to an optical fibre with 9/125  $\mu\text{m}$  core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was ST-connected to a ST-receptacled silicon photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response. In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

- 18 -

**Example 2:**

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at  $\lambda=1300$  nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125  $\mu\text{m}$  core/cladding diameter to an optical fibre with 50/125  $\mu\text{m}$  core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response.

In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor

**Example 3:**

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at  $\lambda=1300$  nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125  $\mu\text{m}$  core/cladding diameter to an optical fibre with 100/140  $\mu\text{m}$  core/cladding diameter. The multimode

- 19 -

(larger core) fibre was cleaved approximately 10 mm from the fusion splice location and mirrored. The singlemode fibre free-end was fusion spliced to one of the sensor ports of the (2X2) coupler. The unused sensor port was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then adhered to a steel cantilever beam with Ciba Geigy Araldite 24 hour epoxy. An electrical strain gauge (ESG) was also adhered to the beam using a cyanoacrylate adhesive, co-located with the fibre optic sensor, in order to compare results. The steel beam was placed in a cantilever load frame and deflected. Dynamic experiments were performed by deflecting the beam tip and releasing. The sensor signal output (vibration) and frequency response (via a Fast Fourier Transform) were compared with the ESG response. In each case the sensor response showed excellent correlation with the ESG response. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

#### Example 4:

A fibre optic modalmetric sensor was constructed using a singlemode pigtailed laser diode operating at  $\lambda=1300$  nm. The laser diode pigtail was fusion spliced to a 1300 nm singlemode, 3 dB (2X2) fibre optic coupler. The sensing region was constructed by fusion splicing an optical fibre with 9/125  $\mu\text{m}$  core/cladding diameter to an optical fibre with 100/140  $\mu\text{m}$  core/cladding diameter. The multimode (larger core) fibre was cleaved approximately 300 mm from the fusion splice location and mirrored. The singlemode fibre free-end was FC-connectorised and connected to a FC receptacled sensor port of the (2X2) coupler. The unused sensor port arm was fractured to minimise end reflections. The remaining output port of the coupler was fusion spliced to a fibre pigtailed InGaAs photodiode. The sensor was then encapsulated in a thin layer of Ciba Geigy Araldite 24

- 20 -

hour epoxy and embedded in a concrete beam. The concrete beam was placed in a three-point bend apparatus and deflected. The response of the sensor showed excellent agreement with the magnitude and frequency of the applied force. The concrete beam was also impacted with a steel hammer and the sensor response showed the expected, high frequency response characteristics. The lead-in/lead-out singlemode fibre showed no significant sensitivity to external perturbations, demonstrating good localisation of the sensor.

Optical devices made by the method of the invention and optical devices according to the invention are useful in a wide variety of applications and fields. Not inclusive, but indicatively, the following examples illustrate some applications in which the fibre optic modalmetric sensor may be used:

- Aerospace structures operate on extremely tight tolerances and safety criteria. As a consequence, aerospace structures are often inspected at frequent intervals using labour intensive non-destructive techniques. Electrical strain gauges and piezo-electrics cannot be incorporated into the structure without detrimental effects and have a limited fatigue life. As a consequence, real-time structural integrity monitoring is rarely achieved in aerospace structures, except perhaps in sophisticated military research projects. The fibre optic modalmetric sensor, alternatively, can be adhered to the inner-surface of aerospace structures, thus not affecting the aerodynamics, and yet provide the following advantages over conventional sensors: they can perform quasi-static or dynamic measurements, have very high fatigue life, are corrosion resistant, are non-conductive, are capable of point or distributed sensing, can be configured to any shape or contour, and a single sensor is capable of monitoring several parameters simultaneously. Furthermore, it is

- 21 -

possible to embed the optical sensor in composite components to perform in-situ monitoring.

- Off-shore oil-rigs are generally routinely inspected by divers or robots for structural integrity. The harsh, corrosive environment renders it nearly impractical to attach conventional sensors to the structure. As a result, cracks or any other form of damage cannot be detected in its early stages and could possibly grow to within catastrophic levels before it is visually found. Electrical strain gauges would require long wire lead lengths to reach the desired sensing region, thus electrical noise would be a large limitation. Piezo-electric sensors have a major limitation in that they are a dynamic material, whereas vibrations in oil-rigs are generally quasi-static ( $< 2$  Hz). In addition, electrical devices are prone to corrosion damage which would limit their lifetime substantially. Fibre optic modalmetric sensors are not only resistant to corrosion, but they could possibly monitor the extent of corrosion of the structure. Lightning strikes would severely effect electrical or conductive devices, whereas optical sensors are generally not affected by this type of strike. The fibre optic modalmetric sensors can be reliably adhered to critical areas of off-shore oil-rigs (ie. underwater support structures) and thus offers the opportunity to monitor the structural integrity in real-time. On-board the oil-rig, fibre optic modalmetric sensors could continuously monitor structural vibrations.
- Naval vessels (ships or submersibles) are generally monitored by divers or in dry docks for structural integrity. The limitations of conventional sensors in this case are the same as those discussed for off-shore oil rigs. Fibre optic modalmetric sensors would be extremely useful for these structures as the world-wide fleet is generally quite old and ageing

- 22 -

rapidly. A particular advantage of a fibre optic modalmetric sensors for use in these structures is the ability to monitor relatively large areas and to localise the sensing regions. Conventional sensors are usually limited in size. The longer/larger sensor types that do exist are usually very expensive. The fibre optic modalmetric sensors, on the other hand, can be configured to any desired length/size with only a marginal increase in cost and complexity.

- Power stations and transformers are critical structures to monitor as they tend to over-heat and have vibrational problems which could result in extremely dangerous explosions. Conventional sensing techniques suffer extreme electrical noise problems when monitoring these structures due to electro-magnetic interference (EMI). Fibre optic modalmetric sensors can easily be adhered to these structures to monitor temperature, vibrations, cracking, strains and stresses, and several other important parameters in real-time, without the noise limitations.

- Insulation degradation of large power equipment is one of the major concerns of electricity supply authorities. Forced outage of a large generator or transformer due to insulation breakdown can cost millions of dollars in repair and outage costs. The potential for generator and transformer outage is ever increasing as a large proportion of the capital equipment in the Australian and international electrical industry is nearing its expected lifetime. Replacement and refurbishment of these major components has significantly slowed down because of economic restraints and many are now operating beyond their expected operational lifetime. Therefore, it is important to closely monitor the insulation condition of these components and determine the remnant life of the electrical generating plant.



- 23 -

Partial discharge (PD) measurements have been one of the most effective diagnostic tools for monitoring the insulation condition of high voltage equipment. In-service measurements of partial discharges in generators and transformers are extremely difficult because of large interference effects from various sources, particularly EMI. Investigations have been carried out in the world to develop reliable detection techniques and devices, however, no successful breakthrough has until now been achieved. The fibre optic modalmetric sensor offers a new technique for PD measurements in the power industry by monitoring minute, high frequency acoustic emission signals in the structure. Machine condition monitoring can be performed simultaneously with the fibre optic modalmetric sensor by low-pass filtering the signal and performing frequency analysis of the structural resonances. The fibre optic modalmetric sensor offers several advantages over other PD detectors currently under development around the world, these include: less complex, small size, ease of use, safer for the high voltage equipment insulation, more reliable for noise discrimination (immunity to EMI) and cost effective.

- Undersea pipelines are generally not monitored at all due to the lack of any reliable and durable sensing techniques. If something goes wrong with a pipeline (ie., cracking, corrosion, etc.) it is usually realised when the output flow is affected. No information is available as to the type and location of the fault. Obviously, this is an inefficient and potentially costly situation. Not only has the flow of goods stopped, but the pipeline has to be pulled up or divers/robots need to go down to have a look for the fault. Undersea pipelines are in a very harsh and corrosive environment. In addition, their lengths can vary from a few meters to several hundred kilometres

- 24 -

- in length. Conventional conductive sensors would have difficulties surviving the environment and because of the long lengths of wire-leads required they would suffer from electrical noise problems. Undersea optical fibre communication cables have proved their capabilities in long-haul ( > 1000 km) applications, therefore optical fibre sensors could be useful in long-haul sensing requirements.
- The chemical and petrochemical industries have an ongoing need to monitor the structural health and integrity of all their reaction and containment tanks/vessels and cylinders. This can be achieved with semi-permanent, conventional techniques but durability and accuracy are essential or false alarms may result. The inherent advantages of the fibre optical modalmetric sensor makes it ideal for this application.
- The measurement of loads currently relies heavily on load cells which are configuration of resistive strain devices. The cells have a characteristic narrow load range within which accuracy and sensitivities are within tolerance. The narrowness of this operating range derives from the non-linearity of the electrical resistance response to strain, a feature which the fibre optic modalmetric sensor overcomes. Hence load cells constructed with fibre optic modalmetric sensor components should be more sensitive at most loads but cover a much broader range off loads. This would result in the current series of load cells being replaced by a single broad-range fibre optical modalmetric sensor cell. An added advantage would be the zero sensitivity of the fibre optic modalmetric sensor cells to electrical noise and harmonic responses to set frequencies of loading.
- Structural integrity monitoring applications in general.
- Machine condition monitoring applications in general.

- 25 -

- Optical signal processing, conditioning, stabilisation and optimisation applications in general.

The fibre optic modalmetric sensor may be used in most applications where conventional sensors such as electrical strain gauges, accelerometers, thermocouples, make-break circuits and piezo-electric sensors are employed or might be employed if they were less limited. Not inclusive, but indicatively, the following examples illustrate some users of the fibre optic modalmetric sensor:

- Road, rail, dam and bridge construction and maintenance firms.
- Owners, operators and insurers of marine vessels.
- Petroleum and petrochemical companies.
- Power, water and fuel facilities.
- Tower owners and operators.
- Aircraft manufacturers and repairers.
- Airfleet operators.
- Automotive industry.
- Non-destructive evaluation firms and equipment manufacturers.
- R&D companies and laboratories.
- Wood pulp and paper manufacturers
- Instrument and sensor manufacturers.
- Sports equipment and facilities manufacturers and operators.
- Off-shore oil rig operators and maintenance firms.
- Mine operators.
- Quality Assurance and safety firms.
- Building management firms.
- Industrial equipment operators and manufacturers.
- Security firms.
- Power plant manufacturers, owners or operators.
- Telecommunications firms or operators.
- Telecommunication components/devices manufacturers.

To date, the use of multimode fibre systems has been greatly limited by their undesired response

- 26 -

characteristics. This significant disadvantage offsets the fibre's advantages of low cost and ease of fabrication. The fibre optic modalmetric sensor overcomes the inherent weaknesses, is easy to fabricate and costs relatively little to assemble.

Such a sensing system would offer low cost and increased safety advantages over existing technologies and has the potential for short to long term installation monitoring in plant, ecological (i.e., undersea) and other environments. Many applications of the fibre optic modalmetric sensor are possible because of its sensitivity, simplicity and cost effectiveness.

Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiment described by way of example hereinabove.

- 27 -

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for producing a sensor, including:  
providing a singlemode optical fibre formed from  
a waveguide material and having a fibre core;  
5 providing a multimode waveguide having a  
waveguide core;  
fusion splicing the singlemode fibre and  
multimode waveguide so that centres of the cores of the  
singlemode fibre and multimode waveguide are aligned and  
10 remain fixed at the splice; and  
cleaving or polishing the multimode waveguide,  
after the fusion splicing, at a desired location spaced  
from the splice to localise the sensor.
2. The method of claim 1 wherein the singlemode  
15 fibre and multimode waveguide are prepared prior to fusion  
splicing by cleaving or polishing ends of the singlemode  
and multimode waveguide to establish flat smooth surfaces  
at the ends of the singlemode fibre and multimode waveguide  
which are to be fusion spliced.
- 20 3. The method of claim 1 wherein the cleaving or  
polishing at the desired location spaced from the fusion  
splice establishes a flat smooth surface at the desired  
location.
- 25 4. The method of claim 3 wherein the flat smooth  
surface at the desired location is coated with a mirroring  
material to reflect radiation back through the multimode  
waveguide and then the singlemode fibre to a detecting  
device.
- 30 5. The method of claim 1 wherein the singlemode  
fibre is coupled to a light source, and a detecting device.
6. The method of claim 1 wherein a plurality of

- 28 -

multimode waveguides and singlemode fibres are fusion spliced in end-to-end relationship to form a quasi-distributed sensor.

7. The method of claim 1 wherein a plurality of  
5 singlemode fibres are fusion spliced to respective multimode waveguides and the plurality of singlemode fibres are connected to a coupler which in turn is connected to a further singlemode fibre to form a multiplexed sensor.
8. The method of claim 1 wherein multimode  
10 waveguide includes at least one optical sensing element.
9. The method of claim 1 including the step of coupling a light source and detector to the singlemode optical fibre.
10. The method of claim 1 including coupling a light  
15 source to the singlemode fibre, fusion splicing a further singlemode fibre to the multimode waveguide at the desired location and coupling a detector to the further singlemode fibre.
11. The method of claim 1 wherein the multimode  
20 waveguide is a multimode fibre.
12. A sensor including:  
a singlemode optical fibre formed from a waveguide material and having a fibre core; and  
a multimode waveguide having a waveguide core,  
25 the multimode optical fibre being fusion spliced to the singlemode optical fibre so that centres of the cores of the singlemode fibre and multimode waveguide are aligned and remain fixed at the splice; and  
wherein the multimode waveguide is cleaved or  
30 polished, after fusion splicing, at a desired location spaced from the fusion splice to localise the sensor.

- 29 -

13. The sensor of claim 12 wherein the cleaving or polishing at the desired location spaced from the fusion splice establishes a flat smooth surface at the desired location.

5 14. The sensor of claim 13 wherein the flat smooth surface at the desired location is coated with a mirror material to localise the sensor.

15 15. The sensor of claim 12 wherein the cleaved or polished multimode waveguide is fusion spliced to a further singlemode fibre which is coupled to a detecting device.

16. The sensor of claim 13 wherein the sensor is coupled to a light source and a detecting device.

15 17. The sensor of claim 16 wherein the light source and detecting device are coupled to the singlemode fibre so that radiation, in use, is launched into the singlemode fibre and propagates along the singlemode fibre and also along the multimode waveguide wherein properties of the radiation are altered due to changes in a parameter which is to be monitored, and the radiation is reflected from the  
20 mirroring material back along the multimode waveguide and singlemode fibre for detection by the detecting device.

25 18. The sensor of claim 12 wherein a light source is coupled to the singlemode fibre for launching radiation into the singlemode fibre, and wherein a further singlemode fibre is fusion spliced to the desired location of the multimode waveguide and a detecting device is coupled to the further singlemode fibre for detecting radiation which is passed through the multimode fibre and which has had a property altered and wherein radiation propagates from the  
30 multimode waveguide into the further singlemode fibre for detection by the detecting device.

- 30 -

19. The sensor of claim 12 wherein the multimode waveguide is a multimode fibre.



1/2

Fig 1

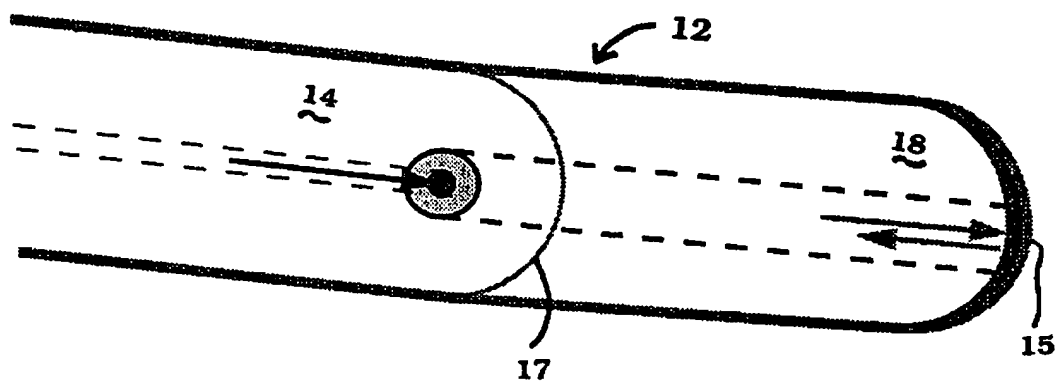
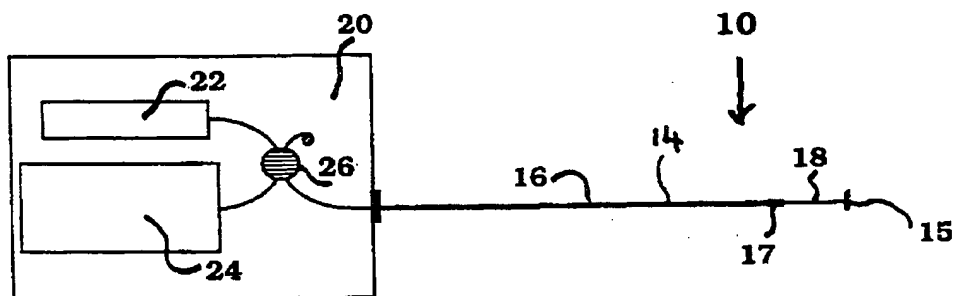


Fig 2



2 / 2

Fig 3

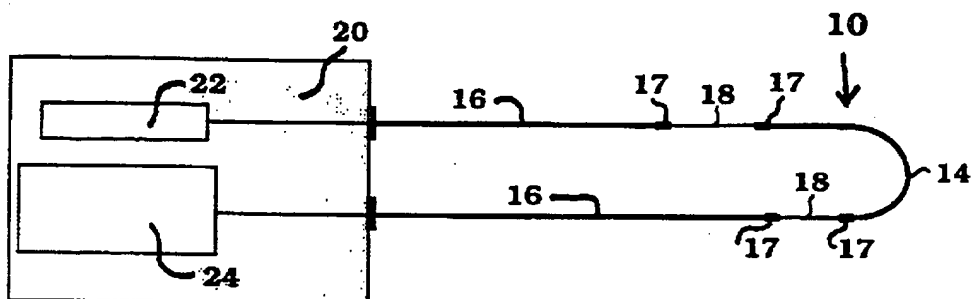


Fig 4

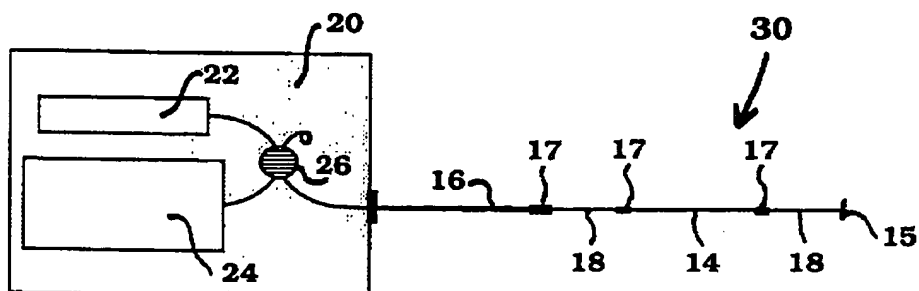
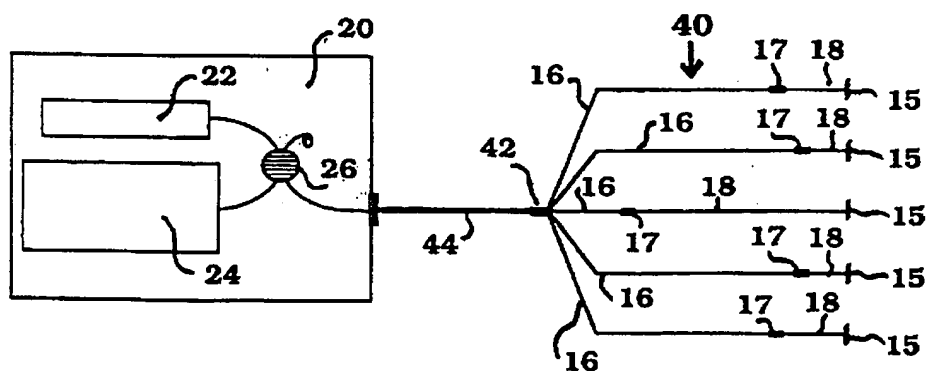


Fig 5



## INTERNATIONAL SEARCH REPORT

International Application No.  
PCT/AU 95/00568

<b>A. CLASSIFICATION OF SUBJECT MATTER</b>		
Int Cl <sup>6</sup> : G01D 5/353, G01H 9/00, G01M 11/00, G01L 1/24, G02B 6/255.		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) IPC G01, G02		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched AU: IPC as above		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) DERWENT: JAPIO: } (Single()Mode)and(Fiber# or Fibre#)and(Fusion()Splic:) ENGINEERING INDEX:		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Patent Abstracts of Japan, P-1192, page 7, JP, 3-25381, A (Sumitomo Electric Ind. Ltd) 4 February 1991 abstract	1,8,11,12,19.
A	US, 5008545, A (ANDERSON ET AL) 16 April 1991 Whole document	
A	Patent Abstracts of Japan, P-1337, page 86, JP, 4-5529, A (FUJIKURA LTD) 9 January 1992 abstract	
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C <input checked="" type="checkbox"/> See patent family annex		
<p>* Special categories of cited documents:</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&amp;" document member of the same patent family</p>		
Date of the actual completion of the international search 1 December 1995		Date of mailing of the international search report 11 DECEMBER 1995
Name and mailing address of the ISA/AU AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (06) 285 3929		Authorized officer  Derek Barnes Telephone No.: (06) 283 2198

## INTERNATIONAL SEARCH REPORT

International Application No.  
PCT/AU 95/00568

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Patent Abstracts of Japan, P-1086, page 114, JP, 2-129611, A (NIPPON TELEGR & TELEPH CORP) 17 May 1990 abstract	
A	Patent Abstracts of Japan, P-569, page 153, JP, 61-270708, A (FURUKAWA ELECTRIC CO LTD) 1 December 1986 abstract	
A	Patent Abstracts of Japan, P-1039, page 124, JP 2-39110, A (NEC CORP) 8 February 1990 abstract	
A	Patent Abstracts of Japan, P-6, page 28, JP 55-17183, A (FUJITSU KK) 6 February 1980 abstract	

**INTERNATIONAL SEARCH REPORT**  
**Information on patent family members**

International Application No.  
**PCT/AU 95/00568**

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report				Patent Family Member			
US	5008545	JP	3-150442	DE	4033546	FR	2653621
END OF ANNEX							